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STEPGRAD
СТЕПГРАД

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INFLUENCE OF EVAPOTRANSPIRATION ESTIMATION METHODS ON IRRIGATION SYSTEM DESIGN

Abstract:
This paper evaluates methods for estimating evapotranspiration (ET) and their influence on irrigation system design, using a case study from Modriča, Republic of Srpska. We compare empirical, physically-based, and remote sensing approaches including Thornthwaite, Hargreaves–Samani, Jensen–Haise, Linacre, McGuinness and FAO Penman–Monteith alongside satellite-derived data from Climate Engine. A multicriteria analysis is employed to rank the methods based on reliability, climatic adaptability, data requirements and complexity. The results demonstrate that the choice of ET estimation method significantly impacts calculated water demand and, consequently, irrigation system design. The study concludes by emphasizing the critical role of method selection in achieving irrigation efficiency and optimizing project costs.

Keywords: evapotranspiration, FAO Penman–Monteith, empirical methods, satellite data, multicriteria analysis

УТИЦАЈ МЕТОДА ЗА ПРОРАЧУН ЕВАПОТРАНСПИРАЦИЈЕ НА ДИМЕНЗИОНИСАЊЕ СИСТЕМА ЗА НАВОДЊАВАЊЕ

Сажетак:
У овом раду анализиране су методе за прорачун евапотранспирације (ЕТ) и њихов утицај на димензионисање система за наводњавање, на примјеру локалитета у Модричи, Република Српска. Упоређене су емпиријске, физички засноване и методе даљинског истраживања укључујући Thornthwaite, Hargreaves–Samani, Jensen–Haise, Linacre, McGuinness и FAO Penman–Monteith, као и сателитски подаци са Climate Engine платформе. Примјењена је мултикритеријумска анализа за рангирање метода у односу на поузданост, климатске услове, доступност података и комплексност примјене. Резултати показују да избор методе значајно утиче на прорачун потреба за водом и, посљедично, димензионисање система за наводњавање. У овом раду се истиче кључна улога адекватног избора методе у постизању ефикасности наводњавања и оптимизацију трошкова пројекта.

Кључне ријечи: евапотранспирација, FAO Penman–Monteith, емпиријске методе, сателитски подаци, мултикритеријумска анализа

1. INTRODUCTION

Contemporary society is increasingly aware of limited water resources, a challenge exacerbated by climate change and growing water demands from population and industry [1]. In this context of water scarcity and the need to enhance agricultural productivity, efficient irrigation systems are critical. The fundamental principle lies in accurately matching water supply to crop demand, quantified as crop evapotranspiration (ET_c). ET_c, the product of reference evapotranspiration (ET_o), a crop coefficient (K_c) and water stress coefficient (K_s), is a primary parameter for defining agricultural water needs and designing irrigation systems.

The design of any engineered irrigation system is a hydraulic translation of agronomic water requirements. The calculated peak ET_c rate directly determines the key design parameters, such as system capacity and pipe dimensions. However, the impact of the chosen ET_o estimation method on the predicted water requirements and the subsequent irrigation system design has not be sufficiently evaluated [1].

A wide array of methods exists to estimate ET_o. Most used are empirical methods due to their low data requirements and simplicity, though this is at the cost of accuracy. Physically-based methods such as FAO Penman-Monteith (PM) equation, consider the full suite of climate drivers and are internationally recognized as a robust standard. However, in many regions, including study area, the comprehensive high-quality meteorological data required for FAO PM are usually unavailable. Remote sensing methods [2], [3] which estimate ET directly from satellite or aerial imagery, offer high spatial resolution and are becoming more accessible. Yet, they can involve processing complexity and may have limitations in temporal resolution.

While extensive literature compares ET estimation methods in terms of their accuracy against lysimeters [4], [5], [6] or the FAO PM standard [7], [8], [9], a critical gap exists in quantifying the downstream *engineering* implications of method selection. Specifically, there is a lack of studies translating methodological differences into tangible impacts on irrigation system design parameters and costs. This study aims to bridge the gap by evaluating the impact of ET_o estimation methods on system design through a case study in Garevac, Modriča. We compare empirical (Thornthwaite, Hargreaves–Samani, Jensen–Haise, Linacre and McGuinness), physically-based (FAO Penman–Monteith**)** and remote sensing methods (Climate Engine data) approaches. Each method is integrated into a standardized hydraulic design model, with the FAO PM serving as the benchmark. The results are compared and analyzed form the perspective of technical design output and economic cost implications.

2. STUDY AREA AND DATA

The study area is located in the municipality of Modriča, within the cadastral municipality of Garevac. It compromises approximately 50 hectares of agricultural land designated for irrigation development (Figure 1). The planned irrigation system is designed for field crop production, specifically corn, wheat, soybeans, and oilseed rape. These crops were identified as the most common in this region based on a survey of local producers [10].

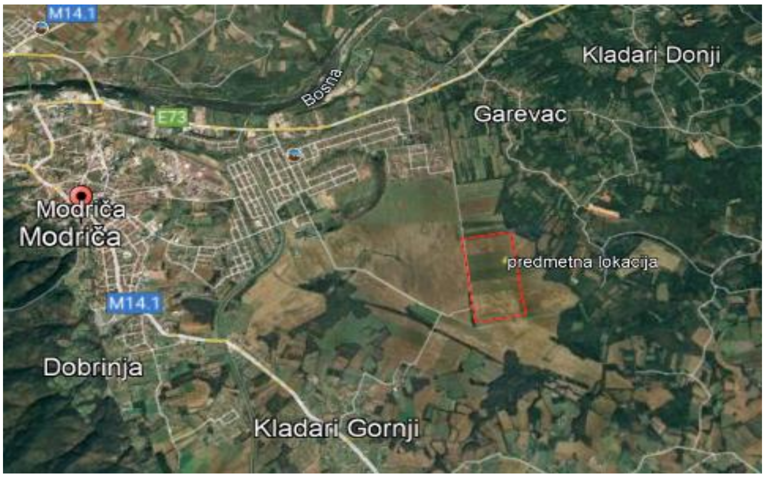

Figure 1. Location of the study area in the Google Earth maps environment (the study area is marked with a red rectangle).

An existing well on-site serves as the water source for irrigation. Its technical characteristics are as follows: a capacity of 42 l/s, a diameter of Ø500 mm, and a total depth of 22 m, with a static water level at 10.83 m depth [11].
The climatic and pedological conditions of the Modriča region are favorable for agricultural, characterized by long growing season, moderate temperature variations, suitable soil structure and beneficial air circulation [12].
Reference evapotranspiration (ET_o) was calculated using multiple approaches for comparative analysis:

- The FAO Penman–Monteith method is used as the benchmark, calculated using a 30 years long meteorological time series from the Slavonski Brod station [10];
- Empirical methods - Thornthwaite, Hargreaves–Samani, Jensen–Haise, Linacre, and McGuinness [15] are selected for their computational efficiency and established use in literature. Input climate data (temperature, precipitation, solar radiation, humidity and wind speed) were sourced from the Climate engine platform [13], [14];
- Remote sensing data – Satellite-derived ET_o and actual evapotranspiration ET_a, along with vegetation indices (Normalized Difference Vegetation Index - NDVI and Enhanced Vegetation Index - EVI) were also obtained from the Climate Engine platform for comparison and context.

Soil infiltration was modelled using the Green–Ampt model [16] with the following site-specific parameters: saturated hydraulic conductivity $K = 1.7\times10^{-5}$ m/s, maximum water content $\omega_{max} = 42$ %, field capacity $\omega_p = 37$ %, wilting point $\omega_{sv} = 13{,}5$ %, initial water content $\omega_o = 25{,}25$ % and capillary suction $H_k = 42$ cm. These parameters were derived from available geological and hydrogeological investigations at the site (Figure 2) [11].

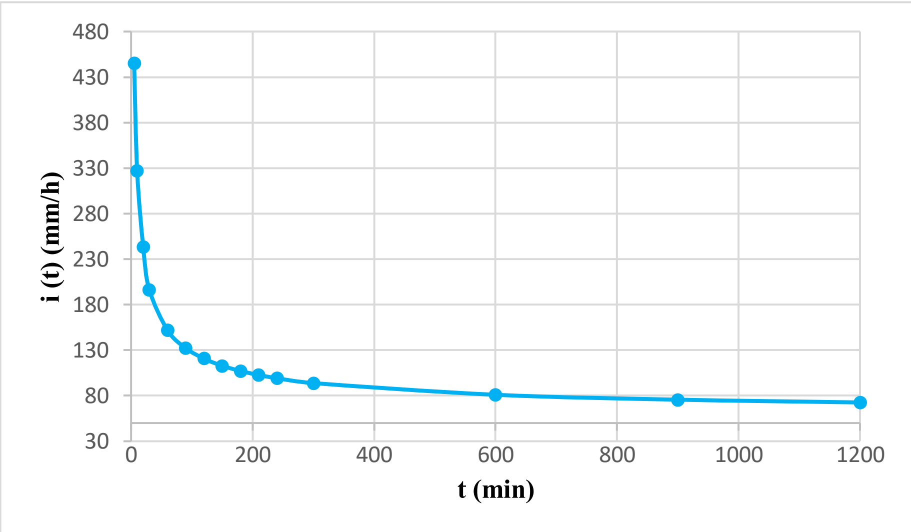

Figure 2. Soil infiltration curve determined using the Green–Ampt method

The minimum net irrigation depth for a wetting zone of 30 cm was calculated to be 38.7 mm [17].

Crop coefficients (K_c) for the analyzed cultures were adopted from the agronomic foundations of the existing project and are presented in Table 1. The analysis was restricted to the crops specified in the local producers' survey [10].

Table 1. Crop coefficients K_c in the growing season [10]

Crop coefficients (-)						
Crop	**April**	**May**	**June**	**July**	**August**	**September**
Corn	0.22	0.56	1.03	1.20	1.1	0.35
Wheat	1.05	1.05	0.25	0	0	0
Soybeans	0.35	0.75	0.75	1.1	1.1	0.75
Oilseed rape	1.05	1.05	0.4	0	0	0.35

3. METHODOLOGY

3.1. METHODS OF EVAPOTRANSPIRATION DATA ACQUISITION AND CALCULATION

The selection criteria for multiple ET estimation methods were based on data availability, ease of application and prevalence in engineering practice and scientific literature.

The chosen empirical methods: Thornthwaite [19], Hargreaves–Samani [20], Jensen–Haise [18], Linacre [21], and McGuinness [15] utilize a limited set of meteorological variables, primarily air temperature and solar radiation, making them particularly suitable for regions with sparse meteorological data. For this study, the calculated potential evapotranspiration (ET_p) values were converted to reference evapotranspiration (ET_0) using established correction factors where applicable [15], [19], [22], insuring comparability with other methods.

The FAO Penman–Monteith equation was employed as the physically-based method. As the internationally accepted standard for calculating ET_0 [23], [24], it integrates energy balance and aerodynamic principles, requiring a more comprehensive set of meteorological data. In this research, the FAO Penman–Monteith method served as the reference benchmark against which the results from empirical and remote sensing methods were validated and compared.

Satellite-derived evapotranspiration data from the Climate Engine platform [13], [14] were incorporated into the analysis. Their dataset includes both reference evapotranspiration (ET_0) and actual evapotranspiration (ET_a) estimates, generated by integrating satellite measurements with meteorological models. These data were used for spatial and temporal comparison with the numerically calculated ET values, with a specific focus on assessing their applicability for engineering design applications.

For all methods, the actual crop evapotranspiration (ET_c) was calculated using the standard formula $ET_c = K_c \times ET_o$, where K_c represents crop coefficients. The K_c values were adopted from the existing agronomic foundations for the site [25]. The analysis was confined to the growing season from April to September, aligning with local agricultural practices and data availability.

3.2. IRRIGATION SYSTEM SELECTION AND DESIGN

A sprinkler irrigation system with portable lateral lines was selected for this analysis, as it is appropriate for the local terrain, predominant field crops and available equipment [10].

The system design followed a standard engineering sequence [26]:

- Determining the irrigation water requirement based on the calculated crop ET;
- Selecting sprinkler type and layout;
- Defining lateral lines specifications (i.e. length and number);
- Calculating system flow rates and operating pressure;
- Assessing system efficiency and total water requirements.

Evapotranspiration served as primary and variable input parameter. A distinct peak irrigation water requirement was calculated for each of the six ET estimation methods. Consequently, six unique design variants were developed, each corresponding to a specific method's output [24], [25].

To isolate the effect of ET input, all other technical parameters - including sprinkler spacing, number of hydrants, network flow rate, pump lift height - were held constant across all variants. This controlled approach ensures that differences in system dimensioning (i.e. pipe diameters, pump specifications) and projected costs are directly attributable to the choice of ET calculation method.

All design variants share the same operational concept: water is extracted from the well via a submersible pump, conveyed through a pressurized pipeline network and delivered to the portable laterals equipped with sprinklers. Hydraulic control elements and water meters are integrated for regulation and monitoring. This design is applicable to the field crops cultivated at the site.

By anchoring the design in a standard sprinkler system methodology and varying only the ET input, this study focuses explicitly on quantifying how the choice of evapotranspiration estimation method influences hydraulic design and cost, rather than on the technical details of the irrigation system itself.

3.3. MULTICRITERIA ANALYSIS OF EVAPOTRANSPIRATION METHODS

A multicriteria analysis (MCA) was employed to evaluate and rank the applied evapotranspiration (ET) estimation methods based on their overall suitability for irrigation system design. Given that ET is the dominant input parameter, this analysis assesses each method's composite impact on the resulting technical and economic dimensions of the system.

The MCA framework facilitates an objective evaluation by incorporating multiple criteria of practical and economic relevance to both project investors and designers. While the FAO Penman-

Monteith method serves as a scientifically rigorous benchmark, it was not granted an *a priori* superior status; its final ranking was determined through the same multi-faceted evaluation process applied to all methods.

Seven key criteria were selected for their direct influence on the system's functionality, economic viability, and practical implementation of the irrigation system. The weights of the criteria in the MCA were determined based on the author's expert judgment, grounded in literature reviews and the practical significance of each criterion for the technical and economic feasibility of the irrigation system. This assignment of specific weights reflects the relative importance of each criterion for project feasibility, ensuring that critical factors, such as water demand and construction costs, have higher influence on the final ranking compared to less impactful criteria, like system complexity. Given the complexity of the topic and limited resources, formal methods for determining weights, such as AHP, were not applied; instead, the weights were assigned according to the importance of each criterion in the context of the project. For future studies, the application of formal methods is recommended to determine the weights more precisely. Both criteria and their weights are presented in Table 2.

To ensure full methodological transparency and reproducibility, the evaluation procedure is explicitly defined as follows. The raw indicator values (both quantitative and qualitative) for each method were transformed into a standardized discrete scoring scale from 1 to 5 (S_i), where 1 represents the least favorable condition and 5 represents the most favorable condition for the system implementation.

Quantitative criteria (such as required water volume, construction costs, and ET_c error) were scored by distributing their raw values into logical ranges. Qualitative criteria were quantified using an expert-based scoring system:

- **Accuracy of input data:** Scored based on data origin (e.g., official measured meteorological data received a score of 5, while model-derived satellite data received a score of 3).
- **Data availability and cost:** Scored based on accessibility (e.g., free open-source platforms received a score of 5, whereas commercial or restricted data received a score of 3).
- **System complexity:** Scored based on the required infrastructural layout (e.g., an optimal arrangement with 12 hydrants received a score of 5, while a highly complex layout with 16 hydrants received a score of 1).

The final weighted score for each evapotranspiration method was calculated using the standard Weighted Sum Model (WSM) formula:

$$Final\ Score = \sum_{i=1}^{n}(Si * wi) \quad (1)$$

where S_i is the assigned discrete score (1–5) for the *i*-th criterion, and w_i is the corresponding criterion weight expressed as a decimal value (with the sum of all weights equal to 1.0).

Table 2. Criteria and assigned weights used in the MCA analysis

Criterion	Weight (%)	Description
1.Required water volume	20	Most critical factor – must fit within the available well capacity
2.Construction costs	20	Directly determines the investment viability
3. Effective land loss	10	Area occupied by physical installations
4. Accuracy of input data	15	Important for irrigation precision
5. Data availability and cost	10	Satellite data are often free, representing a significant advantage
6.Error in ET_c calculation	20	Deviation relative to the reference FAO method
7.System complexity	5	Influences maintenance more than implementation
Total	100	–

The MCA process enables transparent, structured ranking of the methods, synthesizing technical precision, economic implications and practical constraints (including data availability, system costs, implementation complexity and ET calculation errors) into a single comparative assessment.

4. RESULTS AND DISCUSSION

4.1. COMPARISON OF EVAPOTRANSPIRATION METHODS

The calculated average monthly reference evapotranspiration (ET_o) from the seven methods revealed significant quantitative disparities, directly influencing subsequent design parameters. The analysis covers the months from April to September, which correspond to the growing season in the study area. The values and their relative errors compared to the FAO Penman-Monteith benchmark are summarized in Tables 3 and 4 while visual comparison of results is given in Figure 3.

Analysis of the relative errors (Table 4) delineates distinct performance clusters:

- The McGuinness method demonstrated the highest consistency among empirical approaches, with a minimal average relative error of 6.6%. Its reliability was particularly robust during the critical peak summer months (June–August), making it the most suitable empirical alternative for determining peak irrigation demand in the study area.
- Conversely, the Hargreaves–Samani method exhibited a systematic and substantial overestimation, with monthly errors exceeding 60% throughout the growing season. This consistent bias would lead to a significant over-design of irrigation infrastructure if applied without local calibration.
- The Thornthwaite method showed strong seasonal dependency. While its accuracy was lower in April (25.2% error), it achieved remarkable precision in July (4.11% error), suggesting its potential utility for systems designed primarily to meet peak summer demands.
- The Climate Engine Grass Reference Eto data showed considerable deviation, particularly in the early season (~20% error), justifying the use of calculated site-specific ETo over generalized model outputs for engineering design.

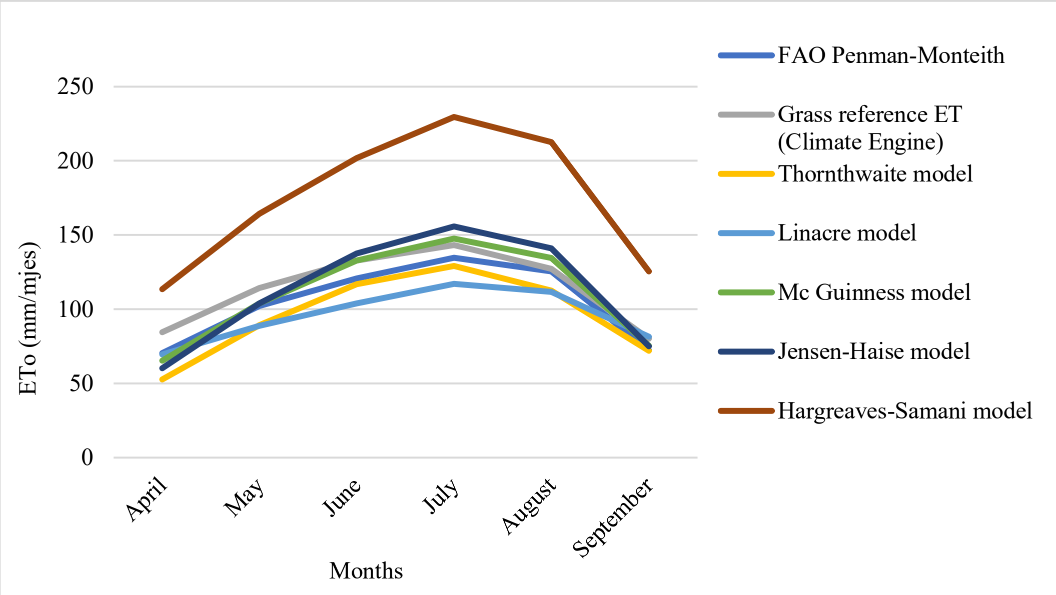

Figure 3. Average monthly ET_o values for the period (1989-2018) during the growing season

Table 3. Average monthly ETo values for the growing season (1989-2018)

Calculation methods	**FAO Penman-Monteith method**	**Climate Engine-Grass**	**Thornthwaite method**	**Linacre method**	**Mc Guinness method**	**Jensen-Haise method**	**Hargreaves-Samani method**
months	**ET_o (mm/month)**						
April	70.44	84.67	52.69	69.54	65.33	60.24	113.51
May	102.12	114.48	89.14	88.87	103.76	103.81	164.13
June	120.63	133.02	116.78	104.13	132.82	137.72	201.77
July	134.70	143.24	129.17	117.10	147.63	155.80	229.58
August	125.34	127.27	112.47	111.56	134.37	141.07	212.47

September	72.52	80.14	71.93	81.41	75.26	75.12	125.65

Results of absolute values of relative error (differences) for ET_o calculation relative to the FAO Penman-Monteith method

Calculation methods	**FAO Penman-Monteith method**	**Climate Engine-Grass**	**Thornthwaite method**	**Linacre method**	**McGuinness method**	**Jensen-Haise method**	**Hargreaves-Samani method**
months	**Reference method**	$\boldsymbol{\varepsilon}[\%] = \left\| \frac{\boldsymbol{ET_{0,Fao\ P-M}} - \boldsymbol{ET_{0,i}}}{\boldsymbol{ET_{0,Fao\ P-M}}} \right\| \cdot \mathbf{100}$					
April	-	20.21	25.20	1.27	7.25	14.48	61.16
May	-	12.10	12.71	12.97	1.61	1.65	60.72
June	-	10.27	3.20	13.68	10.10	14.16	67.26
July	-	6.34	4.11	13.07	9.59	15.66	70.43
August	-	1.54	10.27	11.00	7.20	12.55	69.52
September	-	10.51	0.82	12.25	3.78	3.58	73.26

The observed errors in ET_o estimation translate directly into proportional errors in crop water requirement (ET_c) calculations, as ET_c is derived linearly via crop coefficients. Consequently, the choice of method directly impacts key design parameters. For instance, the systematic overestimation of the Hargreaves-Samani method would result in oversized pumps and pipes, leading to higher initial investment and potentially inefficient operation. In contrast, the closer agreement of the McGuinness and Thornthwaite (summer) methods with the FAO PM benchmark suggests they can yield more economically optimized designs without compromising system adequacy during critical periods.

The satellite-derived ET_a product from the Climate Engine platform was not used for direct design comparison. While valuable for spatial analysis, model-generated ET_a does not account for the specific crop phenology and dynamic crop coefficients (K_c) required for engineering calculations. K_c values are crop-specific and vary from zero (outside the growing season) to a peak mid-season value. Therefore, to ensure accuracy in quantifying irrigation demand, this study derived ET_c through the established pathway of ET_o multiplied by precisely defined, time-dependent K_c values for each crop.

4.2. IMPACT ON IRRIGATION SYSTEM DESIGN

The impact of evapotranspiration method selection was assessed through the resulting irrigation water requirements, the derived hydraulic system module and a comparison of core design parameters. This section examines the discrepancies in these engineering outputs arising from the different ET inputs, rather than provide exhaustive technical specifications.

4.2.1. Impact on the irrigation water requirements

The net irrigation requirements was calculated as the difference between crop evapotranspiration (ET_c) and effective precipitation (P_{eff}) [23]:

$$PV = ET_c - P_{eff} \tag{2}$$

Effective precipitation was estimated using the standard FAO method within the CROPWAT software [23][27], a widely recognized tool for preliminary irrigation planning. The calculation was performed for the four dominant field crops in the study area (corn, wheat, soybeans, and oilseed rape) during the growing season from April to September. For system dimensioning, the maximum monthly water requirement across all crops was adopted, representing the worst-case demand scenario. July consistently emerged as the critical month for all ET methods. The adopted maximum monthly water requirements for each method are presented in Table 5. Their relative deviation from the benchmark (FAO Penman-Monteith) is shown in Table 6, with signs (±) retained to indicate the direction of error (over- or underestimation).

Table 4. Maximum water demand values (mm) determined based on different evapotranspiration estimation methods

Methods of evapotranspiration calculation	Maximum water demand, max PV (mm)
FAO-Penman-Monteith	99.64
Hargreaves-Samani	190.54
Jensen-Haise	124.96
Linacre	78.52
McGuinness	115.15
Thornthwaite	93.00

Table 5. Relative error values (%) of water requirement (PV) calculation using empirical ET_c methods compared to the reference FAO Penman-Monteith method

Methods of evapotranspiration calculation	Relative error ε (%)
FAO-Penman-Monteith	reference method
Hargreaves-Samani	91.22
Jensen-Haise	25.41
Linacre	-21.20
McGuinness	15.56
Thornthwaite	-6.66

The results indicate that the Thornthwaite method yielded water requirements closest to the benchmark, while the Hargreaves–Samani method produced a pronounced overestimation, confirming the trend observed in the ET_o analysis. From an agronomic and risk-averse design perspective, a moderate overestimation is preferable to underestimation, as it reduces the risk of crop water stress. In this context, the McGuinness method presents itself as a robust empirical alternative, showing a consistent and acceptable positive bias.

4.2.2. The impact on the system hydraulic module

The system's hydraulic module was calculated from the adopted maximum water requirements. In accordance with FAO recommendations for addressing limited long-term data, these requirements were increased by a 10% safety factor.

The hydraulic module (mm/day) is the fundamental parameter for determining system flow rates, irrigation schedules, and the sizing of all components. As shown in Table 7, the module calculated for each ET method varies significantly, demonstrating the direct and substantial impact of methodological choice on core engineering specifications.

Table 6. System hydraulic module values depending on the applied evapotranspiration calculation method

Methods of evapotranspiration calculation	Hydraulic module of the system q_s (mm/day)
FAO-Penman-Monteith	4.16
Hargreaves-Samani	7.95
Jensen-Haise	5.22
Linacre	3.28
McGuinness	4.81
Thornthwaite	3.88

A higher evapotranspiration estimate translates directly into a larger hydraulic module, requiring greater system capacity. Reflecting the earlier findings, the Hargreaves–Samani method produced the highest module, demanding the most robust (and costly) system design. The Linacre and Thornthwaite methods resulted in the lowest modules, indicating a more conservative hydraulic demand.

4.2.3. Comparative analysis of system sizing results

Based on the defined hydraulic modules, six distinct design variants were developed, with the ET estimation method as the sole variable. All other parameters—plot layout, system type, sprinkler selection, and irrigation efficiency—remained constant to isolate the effect of ET input.

While detailed hydraulic calculations (e.g., nodal pressures, pipe sizing, head losses) were performed for each variant, they are not presented exhaustively here. These calculations form the technical backbone of the design and were used to generate comparable system specifications for each method.

The design process culminated in comprehensive technical documentation, including CAD schematics for each variant. These drawings detailed the pump station location, hydrant and lateral layout, valve chamber placement, and plot subdivision, all coordinated to ensure optimal field coverage.

Furthermore, longitudinal pipeline profiles were generated to analyze terrain adaptation, pipe diameter transitions, and pressure losses. These graphical outputs were critical for verifying the practical layout and efficiency of each design.

This detailed technical package provided the essential basis for two subsequent steps: (a) preparing accurate Bills of Quantities (BoQ) for cost estimation and (b) supplying the objective inputs for the Multicriteria Analysis (MCA), which evaluates the holistic impact of each ET method on system design and economics.

Due to their scale and technical nature, the full CAD drawings are not reproduced in this paper but constitute the foundational engineering work of the study. It is noted that only hydrotechnical components were analyzed, as architectural, structural, or electrical designs are not influenced by the choice of ET method. This focused approach ensures a clear and transparent analysis of the core irrigation system parameters affected by evapotranspiration estimation.

4.2.4. Techno-economic analysis

The techno-economic analysis focuses on the hydrotechnical components of the irrigation system, quantifying how the choice of ET estimation method translates into total project cost.

The results, summarized in Figure 4, present the total cost for each design variant and its percentage deviation from the cost derived using the FAO Penman-Monteith benchmark.

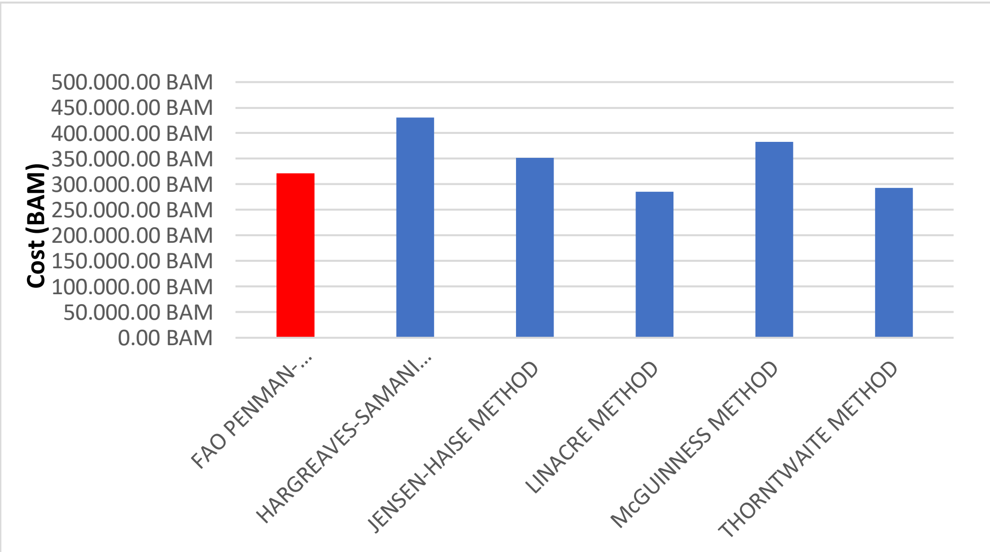

Figure 4. Visual representation of the techno-economic analysis results

Table 7. Comparison of irrigation system costs relative to the reference project costs (FAO Penman-Monteith)

Methods of evapotranspiration calculation	**ε (%) relative error - deviation in project costs from the reference project**	**Value in REFERENCE PROJECT**
FAO-Penman-Monteith	reference method	-
Hargreaves-Samani	33.97	MORE EXPENSIVE 34%
Jensen-Haise	9.57	MORE EXPENSIVE 9.6%
Linacre	-11.18	CHEAPER 11.2%
McGuinness	19.29	MORE EXPENSIVE 19.3%
Thornthwaite	-8.91	CHEAPER 8.91%

The analysis reveals a pronounced economic impact: methods that overestimated water requirements, notably Hargreaves–Samani and McGuinness, led to significantly higher costs—34% and 19.3% above the reference, respectively. In contrast, methods yielding lower ET estimates, such as Linacre and Thornthwaite, resulted in cost reductions relative to the benchmark.

These findings underscore a critical trade-off in irrigation design which is maximizing technical safety through overestimation incurs a substantial economic penalty, while methods closer to the benchmark can yield more cost-efficient designs. Therefore, selecting an optimal method requires balancing agronomic reliability, economic feasibility, and practical constraints—a multi-faceted evaluation performed through the subsequent Multicriteria Analysis (MCA).

4.3. MULTICRITERIA ANALYSIS

The Multicriteria Analysis (MCA) provided a composite evaluation of the six evapotranspiration methods based on their weighted performance across technical, economic, and practical project criteria (defined in Section 3.3, Table 2). The cumulative weighted scores for each method are presented in Table 10.

Before presenting the final weighted scores, Table 9. presents the original, non-normalized values of all criteria for each evapotranspiration method, which served as the basis for the subsequent evaluation process.

Table 8. Original (non-normalized) values of criteria for evapotranspiration methods

	Methods of evapotranspiration calculation					
Criterion	**FAO Penman-Monteith**	**Hargreaves-Samani**	**Jensen-Haise**	**Linacre**	**McGuinness**	**Thornthwaite**
1. Required water volume (max flow in l/s)*	40.44	74.67	52.89	34.22	46.67	37.33
2. Construction costs (BAM)	321.094	430.161	351.819	285,181	383,045	292,494
3. Effective land loss (ha)	3.51	2.35	3.03	3.11	3.12	2.33
4. Accuracy of input data	Official measured data	Satellite derived data	Satellite derived data	Satellite derived data	Satellite derived data	Satellite derived data
5. Data availability and cost	Commercial (paid access)	Open-source (free)	Open-source (free)	Open-source (free)	Open-source (free)	Open-source (free)
6. Error in ETc calculation (%)	0.00 (Reference)	64.27	9.84	10.20	6.27	10.54
7.System complexity (hydrant layout)	14 hydrants (complex)	12 hydrants (favorable layout)	9 hydrants (suboptimal layout)	12 hydrants (suboptimal layout)	16 hydrants (most complex)	12 hydrants (optimal layout)

(Note: Available well capacity is 42 l/s)*

The 'Effective land loss' criterion varies among methods due to differences in the dimensions and layout of micro-parcels within the total irrigation area (50 ha). Although the same irrigation method was applied, the different evapotranspiration values influence the optimal arrangement of hydrants, manholes, and distribution network, resulting in varying land area occupied by infrastructure for each variant. Due to the scope limitations of this study, only summarized results are presented, focusing on the key differences in layout efficiency rather than providing a full comparison of all possible arrangements.

Table 9. Weighted scores of the irrigation projects depending on the evapotranspiration calculation method

	Methods of evapotranspiration calculation					
Criterion	**FAO Penman-Monteith**	**Hargreaves-Samani**	**Jensen-Haise**	**Linacre**	**McGuinness**	**Thornthwaite**
1.	0.8	0.2	0.2	1	0.2	1
2.	0.6	0.2	0.4	1	0.4	0.8
3.	0.1	0.5	0.3	0.2	0.2	0.5
4.	0.75	0.45	0.45	0.45	0.45	0.45
5.	0.3	0.5	0.5	0.5	0.5	0.5
6.	1	0.2	0.6	0.2	0.8	0.4
7.	0.15	0.2	0.2	0.15	0.05	0.25
Total score	**3.7**	**2.25**	**2.65**	**3.5**	**2.6**	**3.9**

This integrated ranking yields several key conclusions:

- The Thornthwaite method achieved the highest overall score due to the optimal balance between low water leading to cost-efficiency, sufficient accuracy during summer months and straightforward application with minimal data requirements. This makes it the most suitable choice for resource-constrained projects in the study area.
- The FAO Penman–Monteith ranked second, reflecting its high technical precision. However, its demanding data prerequisites and associated complexity limit its practicality for routine implementation where such data are scarce.
- The Linacre method emerged as a viable compromise, offering moderate accuracy with very low implementation complexity and cost.
- The Hargreaves-Samani, Jensen–Haise, and McGuinness methods received lower overall scores, primarily due to a poor balance between their systematic overestimation (driving high costs) and their practical advantages.

The MCA demonstrates that the optimal ET method for irrigation design should be selected through a holistic evaluation of project-specific constraints and objectives, not solely on theoretical accuracy. For the conditions prevalent in Modriča, characterized by limited meteorological data and a need for cost-effective solutions, the Thornthwaite method presents the most acceptable practical compromise. While the FAO Penman-Monteith remains the indispensable scientific benchmark, the MCA provides a transparent, structured framework to guide the selection of the most appropriate applied method for a given engineering context.

Although a formal sensitivity analysis of the MCA results with respect to criterion weights was not performed, it is acknowledged that the final ranking depends on the assigned weights. In this study, the MCA was intended as a supporting tool to highlight the relative performance of ET estimation methods rather than to establish an absolute hierarchy. Future research could include sensitivity analysis to evaluate how variations in weights affect method ranking under different project priorities.

5. CONCLUSIONS AND RECOMMENDATION

This study aimed to identify the most suitable evapotranspiration (ET) estimation method for irrigation system design, balancing scientific accuracy with practical constraints such as data availability, computational demand, and economic feasibility.

The key finding is that the choice of ET method has a direct and significant impact on both the technical dimensioning and the total cost of an irrigation system. While the FAO Penman-Monteith method remains the essential scientific benchmark, its comprehensive data requirements limit its practicality in many real-world settings.

The Multicriteria Analysis (MCA), evaluating six methods across seven technical, economic, and practical criteria, identified the Thornthwaite method as the optimal choice for the Modriča region. It achieved the highest overall score by offering a favorable balance: it provided sufficient accuracy, particularly during the critical summer months, while excelling in simplicity, low data needs, and cost-effectiveness. Although the McGuinness method showed the closest numerical correlation to FAO Penman-Monteith for ET_o, its tendency towards overestimation resulted in higher system costs, reducing its overall suitability in the MCA framework.

Therefore, the study concludes that empirical methods, when rigorously evaluated, are valid and rational alternatives to the reference standard. The selection process must be guided by a project-specific multicriteria framework that weighs accuracy against practical constraints.

Summarizing all of the above, some recommendation could be drawn:

1. For irrigation planning in the Modriča region and similar contexts with limited meteorological data, the Thornthwaite method is recommended as the preferred empirical approach for initial design and feasibility studies.
2. The proposed MCA framework should be adapted and applied in other major agricultural regions of Bosnia and Herzegovina (e.g., Herzegovina, Semberija, Posavina). Conducting such region-specific analyses is crucial for validating and calibrating empirical methods across different climatic zones, thereby building a robust national toolkit for efficient irrigation planning.
3. Engineers and planners should adopt a two-tiered verification approach: using a locally validated empirical method for preliminary design, while reserving the FAO Penman-Monteith standard for final validation where sufficient data exist.

This research confirms that optimal irrigation design requires moving beyond a singular focus on the most accurate ET method. Instead, it advocates for a decision-driven engineering process, where method selection is guided by a transparent multicriteria analysis tailored to local data, economic constraints, and project goals. While the FAO Penman-Monteith is the unchallenged reference standard, a context-sensitive multicriteria evaluation enables the selection of reliable, efficient, and practical ET estimation methods, optimizing irrigation system design under real-world constraints.

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